511 keV Gamma Ray from Moduli Decay in the Galactic Bulge

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Abstract

We show that the $e^+ + e^-$ decay of a light scalar boson of mass $1 - 10$ MeV may account for the fluxes of 511 keV gamma ray observed by SPI/INTEGRAL. We argue that candidates of such a light scalar boson is one of the string moduli or a scalar partner of the axion in a supersymmetric theory.

1   Introduction

It has been known in the superstring theory that the compactification with extra-dimensional fluxes stabilizes some moduli in supersymmetric (SUSY) string vacua [1]. It is not yet, however, clear if all of the moduli fields in the sting vacua are stabilized by the flux compactifiction. Therefore, it is a very important task to search a possible evidence for light scalar bosons. In this letter we point out that the 511 keV gamma-ray emission line from the galactic bulge measured by the SPI spectrometer on the space observatory INTEGRAL [2] is explained by the $e^+ + e^-$ decay of a (pseudo)scalar boson of mass $O(1)$ MeV.[1] We also argue that such a light boson can be identified with one of the string moduli or with a scalar partner of the Peccei-Quinn axion field in a SUSY theory. We also stress that the gauge-mediation model with a light gravitino of mass $O(1)$ MeV [4] is very interesting, since the above particles acquires most likely their masses of the order of the gravitino mass $m_{3/2}$ if they survive the flux compactification.

2   The $\phi \to e^+ + e^-$ decay

We consider a scalar boson ϕ which has a Yukawa coupling to the electron as

$$\mathcal{L} = \frac{m_e}{M_*} \bar{e} e \phi. \tag{1}$$

If the ϕ is one of the string moduli, the M_* is of the order of the gravitational scale, $M_* \simeq M_G \simeq 2.4 \times 10^{18}$ GeV [5], and if it is a scalar partner (saxion) of the axion, $M_* \simeq F_a$ where F_a represents the breaking scale of the Peccei-Quinn symmetry. The decay width is given by

$$\Gamma(\phi \to e^+ + e^-) \simeq \frac{1}{8\pi} \left(\frac{m_e}{M_*}\right)^2 m_\phi, \tag{2}$$

and we get the lifetime as

$$\tau(\phi \to e^+ + e^-) \simeq 2 \times 10^{11} \left(\frac{M_*}{10^{16}\text{GeV}}\right)^2 \left(\frac{\text{MeV}}{m_\phi}\right) \text{ yr.} \tag{3}$$

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[1]The possibility of the 511keV gamma-ray emission due to annihilation of dark matter particles was pointed out in Ref. [3].

The lifetime of the ϕ boson should be longer than the age of the universe ($\simeq 1.3 \times 10^{10}$ yr) to give a significant flux of the gamma ray, which leads to a constraint

$$M_* \gtrsim (2.5 - 8.1) \times 10^{15} \text{GeV} \qquad \text{for } m_\phi \simeq 1 - 10 \text{ MeV}. \tag{4}$$

Here we assume that the scalar ϕ does not have a direct coupling to photons. The decay into neutrinos is negligible because of chirality suppression.

3 The energy density of the ϕ boson

It is quite natural to consider that the ϕ boson has a large classical value ϕ_0 of the order M_* at the end of inflation. The ϕ starts a coherent oscillation when the Hubble constant of the universe reaches at the mass of the boson, m_ϕ. The energy density of the coherent oscillation easily exceeds the critical density of the universe [6, 7, 8], which leads to a serious cosmological problem (moduli problem). The thermal inflation [9] is the most promising mechanism to dilute the energy density of the ϕ oscillation and hence solve the moduli problem. We estimated in [10, 11] the energy density, Ω_ϕ, after the thermal inflation. The Ω_ϕ in the present universe is given by

$$\Omega_\phi \gtrsim 4.0 \times 10^{-4} \left(\frac{\kappa M_*}{M_G} \right)^2 \left(\frac{m_\phi}{\text{MeV}} \right)^{-3/14}, \tag{5}$$

for $m_\phi \lesssim 10$ MeV. Here, we have taken $h \simeq 0.7$ (h: Hubble constant in units of 100km/sec/Mpc) in eq. (20) of Ref. [10] and assumed the initial amplitude of the ϕ to be $\phi_0 = \kappa M_*$ with κ being $O(1)$ constant. The lowest density is realized for the reheating temperature after the thermal inflation $T_R \simeq 10$ MeV (see Appendix and [10] for details).

4 The flux of the 511 keV gamma ray

Now we estimate the 511 keV gamma ray flux from the Galactic center. It was shown in Ref. [12] that $e^+ + e^-$ decay of the dark matter particle of mass $m_d \sim O(1 - 100)$ MeV can produce the 511 keV line emission observed by SPI/INTEGRAL, through e^+ and (background) e^- annihilation. Given a density Ω_ϕ, a mass m_ϕ and a lifetime τ_ϕ of the scalar particle, the 511 keV gamma ray flux Φ_{511} is estimated as [12, 13]

$$\Phi_{511} \sim 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1} \Omega_\phi \left(\frac{10^{27} \text{ sec}}{\tau_\phi} \right) \left(\frac{\text{MeV}}{m_\phi} \right), \tag{6}$$

where we have used the present dark matter density $\Omega_{\text{dark}} \sim 0.3$ and the halo density profile $\rho_{\text{halo}} \sim 1/r^{1.2}$[12] ($r$: distance from the Galactic center). Using eqs.(3) and (5) we obtain

$$\Phi_{511} \gtrsim 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1} \kappa^2 \left(\frac{m_\phi}{\text{MeV}}\right)^{-3/14}. \tag{7}$$

It should be remarkable that the prediction of the flux is independent of M_* and weakly depends on the mass of the scalar field. Notice that the observed flux is [2]

$$\Phi_{511} = 9.9^{+4.7}_{-2.1} \times 10^{-4} \text{cm}^{-2} \text{ sec}^{-1}. \tag{8}$$

We see, from eq.(7), that the positrons emitted by the decay of ϕ in the Galactic bulge explain naturally ($\kappa \simeq 1$) the observed fluxes of the 511 keV line gamma ray if the thermal inflation maximally dilutes the scalar field density.

5 Conclusions

We have shown that the $e^+ + e^-$ decay of a light scalar particle of mass $O(1)$ MeV diluted by the thermal inflation is capable of producing 511 keV gamma rays observed by the SPI/INTEGRAL.

Since the scalar field does not have a direct coupling to photons in the present model, the two photon decay ($\phi \rightarrow 2\gamma$) takes place at most through one-loop corrections and hence its branching ratio is less than $\sim 10^{-6}$ for $m_\phi \sim 1$ MeV, which is well below the present observed gamma ray background [14]. However, the photon flux is only one or two oder of magnitude smaller than the current limit for larger mass ~ 10 MeV. The detection of line gamma rays with energy $m_\phi/2$ by future experiments will confirm the present model, since the line gamma rays emitted by this process is distinctive of the model. On the other hand, Beacom *et al.* [15] pointed out that "internal bremsstrahlung" emission ($\phi \rightarrow e^+ e^- \gamma$) exceeds the observed diffuse gamma ray flux from the Galactic center unless $m_\phi \lesssim 40$ MeV. This is one of the reason why we have assumed $m_\phi \simeq 1 - 10$ MeV.

We consider that a good candidate for such a light scalar particle is one of the string moduli for $M_* \simeq M_G$. However, we also stress that the gamma ray flux is independent of M_* as long as it satisfies eq.(4). Thus, the saxion is another candidate if the Peccei-Quinn scale $F_{PQ} = M_*$ is $\sim 10^{15}$ GeV. Notice that since the efficient thermal inflation requires

the reheating temperature as low as $O(1)$MeV the axion density is also diluted. However, as shown in [16] the axion with $F_{PQ} \sim 10^{15}$ GeV explains the dark matter density of the universe for the reheating temperature of $O(1)$ MeV.[2] Therefore, the axion may be the dark matter in the present universe.

The above particles most likely acquire masses of the order of the gravitino mass $m_{3/2}$. The $O(1)$ MeV mass required in the present scenario is expected in the framework of gauge mediation models of SUSY breaking [4].

As for baryon density of the universe, the low reheating temperature makes baryogenesis very hard in general. However, we consider that the late-time Affleck-Dine mechanism [17] may work [18, 19]. [3]

Appendix

In this appendix we estimate the moduli density after the entropy production by the thermal inflation. The moduli density before the thermal inflation is written as

$$\frac{\rho_\phi}{s_i} \simeq \frac{m_\phi^2 \phi_0^2}{T_\phi^3} \simeq 10^{7.5} \text{ GeV} \left(\frac{m_\phi}{\text{MeV}}\right)^{1/2} \left(\frac{\phi_0}{M_G}\right)^2, \tag{9}$$

where s_i is the entropy density before the thermal inflation and ϕ_0 and $T_\phi \simeq \sqrt{m_\phi M_G}$ is the amplitude and the cosmic temperature when the moduli field starts to oscillate.

According to Refs. [10, 11], we adopt the following potential of the flaton χ which is responsible for the thermal inflation:

$$V(\chi) = V_0 + (T^2 - m_0^2)|\chi|^2 + \frac{\lambda^2}{M_G^2}|\chi|^6 \tag{10}$$

where T is the temperature, m_0 is the order of the electroweak scale, λ is a coupling constant, and $V_0 \simeq \lambda^{-1} m_0^3 M_G$. For $T > m_0$ the potential takes minumum at $\chi = 0$. Moreover, if $T < V_0^{1/4}$, the vacuum energy V_0 dominates over the radiation energy of the cosmic plasma. Thus, for $m_0 < T < V_0^{1/4}$ an inflation (therml inflation) takes place. The thermal inflation produces enormous entropy with temperature T_R after the flaton χ

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[2]The present axion density is estimated as $\Omega_a \simeq \theta^2 (F_a/10^{15}\text{GeV})^2 (T_R/10\text{MeV})$, where F_a is the Peccei-Quinn scale and $F_a\theta$ with $\theta \sim O(1)$ is the initial amplitude of the coherent axion oscillation.

[3]The Affleck-Dine leptogenesis [20] may also work if the LH_u flat direction is used with a large cutoff scale.

decay, and the ratio of the final entropy s_f to initial entropy s_i is estimated as

$$\Delta \equiv \frac{s_f}{s_i} = \frac{(4/3)V_0/T_R}{s_i} \simeq \frac{V_0}{T_R m_0^3} \simeq \lambda^{-1}\frac{M_G}{T_R}. \tag{11}$$

Then, the moduli density is diluted by the entropy production as

$$
\begin{aligned}
\Omega_\phi &= \left(\frac{\rho_\phi}{s_f}\right)\left(\frac{s_0}{\rho_{cr,0}}\right) = \left(\frac{\rho_\phi}{s_i}\right)\left(\frac{s_0}{\rho_{cr,0}}\right)\frac{1}{\Delta} \\
&\simeq 4\times10^{-4}\lambda\left(\frac{m_\phi}{\mathrm{MeV}}\right)^{1/2}\left(\frac{\phi_0}{M_G}\right)^2\left(\frac{T_R}{10\mathrm{MeV}}\right),
\end{aligned}
\tag{12}
$$

where $\rho_{cr,0}$ and s_0 is the present critical and entropy density. Notice that this value is almost the same as the minimum moduli density given by eq. (5) for $m_\phi \simeq 1$ MeV.

However, the moduli dilution by the thermal inflation is not so simple because the field value that gives the minimum of the moduli potential is shifted by the Hubble induced mass term during the thermal inflation. This shift produces a new oscillation with amplitude $V_0\phi_0/(m_\phi M_G)^2$, which leads to

$$\Omega_\phi \simeq 10^{-6}\lambda^{-1}\left(\frac{m_\phi}{\mathrm{MeV}}\right)^{-2}\left(\frac{\phi_0}{M_G}\right)^2\left(\frac{T_R}{10\mathrm{MeV}}\right)\left(\frac{m_0}{\mathrm{GeV}}\right)^3. \tag{13}$$

Therefore, the total moduli density is determined from contributions of both eqs. (12) and (13). Assuming that the falton decays into two gluons ($T_R \simeq 10^{-3}\lambda^{1/2}m_0$), we can obtain the minimum moduli density (5) by varing m_0 and λ [10].

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